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The Impact of Transit Observations on Planetary Physics

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Abstract. We highlight the importance of transit observations on understanding the physics of planetary atmospheres and interiors. Transmission spectra and emission spectra of atmospheres allow us to characterize these exotic atmospheres, which possess TiO, VO, H₂O, CO, Na, and K, as principal absorbers. We calculate mass-radius relations for water-rock-iron and gas giant planets and examine these relations in light of current and future transit observations. A brief review is given of mechanisms that could lead to the large radii observed for some transiting planets.

1. Introduction

The blanket term “hot Jupiter” or even the additional term “very hot Jupiter” belies the diversity of these highly irradiated planets. Each planet likely has its own unique atmosphere, interior structure, and accretion history. The relative amounts of refractory and volatile compounds in a planet will reflect the parent star abundances, nebula temperature, total disk mass, location of the planet’s formation within the disk, duration of its formation, and its subsequent migration (if any). This accretion history will give rise to differences in core masses, total heavy elements abundances, and atmospheric abundance ratios. Through transit observations we are able to probe nearly *20 orders of magnitude* in pressure in these planets, as seen in Figure 1, from the outer reaches of the escaping atmosphere to the high pressures of dense central cores.

Since atmospheric and interior physics are both quite large topics, here we will focus specifically on the atmospheres of close-in giant planets at photospheric pressures, which *Spitzer* data is allowing us access to, as well as the structure and mass-radius relations of Earth-like to gas giant planets. At least 21 gas giants are now known, as well as a possible Neptune-class planet, with even smaller planets on the horizon.

2. Atmospheres

Since irradiation is perhaps the most important factor in determining the atmospheric properties of these planets, we examine the insolation levels of the 20 known transiting planets. We restrict ourselves to those planets more massive than Saturn, and hence for now exclude treatment of the “hot Neptune” GJ 436b. Figure 2 illustrates the stellar flux incident upon the planets as a function of both planet mass (Figure 2*a*) and planet surface gravity (Figure 2*b*). In these

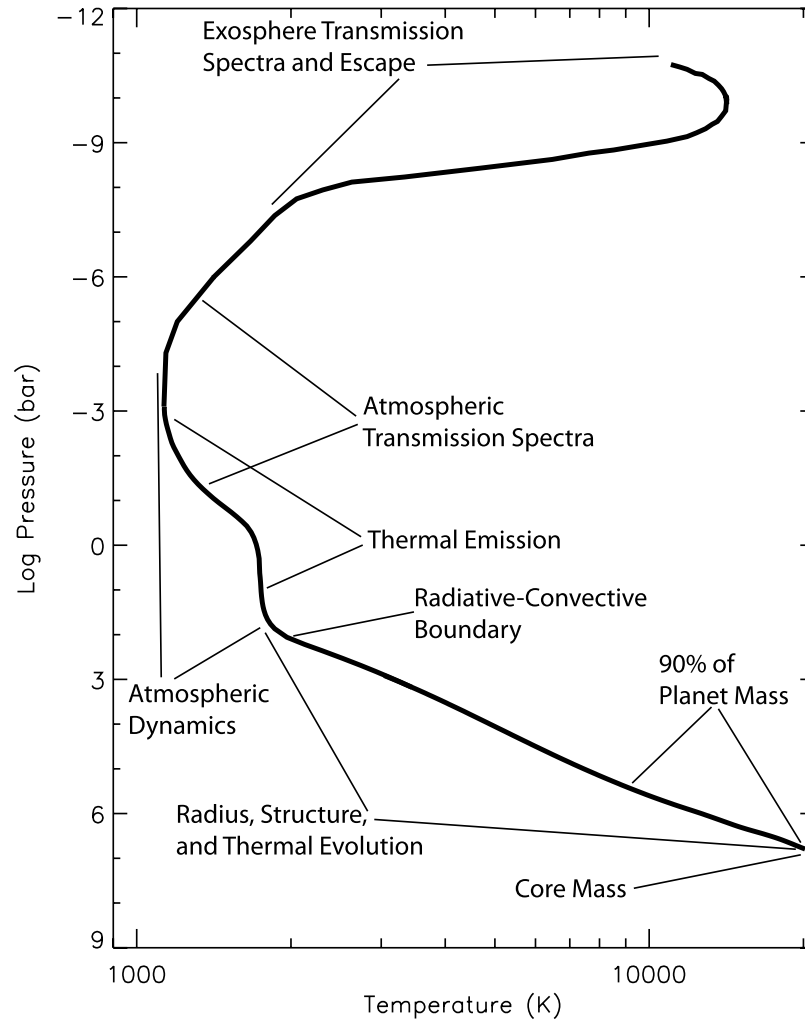
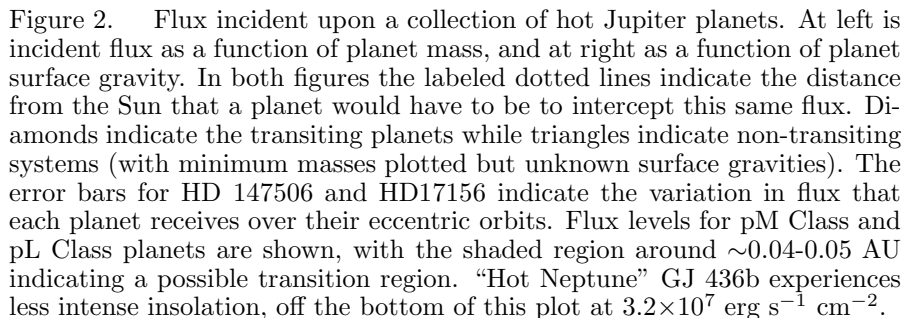


Figure 1. Exosphere (adapted from Yelle 2004), atmosphere (Fortney et al. 2005), and interior (Fortney et al. 2007b) P - T profile for a generic HD 209458b-like planet.

plots diamonds indicate transiting planets and triangles indicate other interesting hot Jupiters, for which *Spitzer Space Telescope* data exist, but which do not transit. The first known transiting planet, HD 209458b, is seen to be fairly representative in terms of incident flux.

Fortney et al. (2007a) argue that based on the examination of few physical processes that two classes of hot Jupiter atmospheres emerge. Equilibrium chemistry, the depth to which incident flux will penetrate into a planet's atmosphere, and the radiative time constant as a function of pressure and temperature in the atmosphere all naturally define two classes these irradiated planets. Those planets that are warmer than required for condensation of titanium (Ti) and vanadium (V)-bearing compounds will possess a temperature inver-



sion at low pressure due to absorption of incident flux by TiO and VO (a stratosphere, as found by Hubeny et al. 2003 and Fortney et al. 2006b), and will appear “anomalously” bright in secondary eclipse at mid-infrared wavelengths. Furthermore, these planets will have large day/night effective temperature contrasts *and* will also be comparatively easy to detect at optical wavelengths due to thermal emission. We will term these very hot Jupiters the “pM Class,” meaning gaseous TiO and VO are the prominent absorbers of optical flux, similar to M dwarfs. Planets with temperatures below the condensation temperature curve of Ti and V bearing compounds will have relatively smaller secondary eclipse depths in the mid infrared, significantly smaller day/night effective temperature contrasts, and atmospheric dynamics will lead to a complex redistribution of absorbed energy. We term these hot Jupiter planets the “pL Class,” since once TiO/VO are removed, alkalis become the prominent optical absorbers (Burrows, Marley, & Sharp 2000), similar to L dwarfs. Published *Spitzer* data are consistent with this picture. In the late stages of the submission of this contribution, Knutson et al. (2007) used *Spitzer* IRAC to find evidence for a temperature inversion for HD 209458b at secondary eclipse, potentially

attributed to TiO/VO opacity (Burrows et al. 2007c). The inversions for planets HD 209458b (Knutson et al. 2007) and HD 149026b (Harrington et al. 2007, as was predicted by Fortney et al. 2006b) support the theory of Fortney et al. (2007a). Burrows et al. (2007a) have recently advanced a similar view.

A key difference between the atmospheres of the pL Class planets and pM Class planets is the pressure at which the absorption and emission of flux occurs (Fortney et al. 2007a). This can be shown by plotting the pressure that corresponds to a calculated brightness temperature. This is shown as a function of wavelength in Figure 3. In general thermal emission arises from a characteristic pressure level roughly an order of magnitude greater in a pL Class atmosphere than in a pM Class atmosphere.

What effect this may have on the dynamical redistribution of energy in a planetary atmosphere can be considered after calculation of the radiative time constant, τ_{rad} . In the Newtonian cooling approximation a temperature disturbance relaxes exponentially toward radiative equilibrium with a characteristic time constant. At photospheric pressures this value can be approximated by

$$\tau_{\text{rad}} \sim \frac{P}{g} \frac{c_p}{4\sigma T^3}, \quad (1)$$

where σ is the Stefan-Boltzmann constant and c_p is the specific heat capacity (Showman & Guillot 2002). In Figure 4 we show detailed calculations of τ_{rad} as a function of pressure alongside the radiative-convective equilibrium profiles from which they were generated (Fortney et al. 2007a). Although these time constants are nearly equivalent in the dense lower atmosphere, they are significantly different in the thinner upper atmosphere that one is sensitive to from mid-infrared observations.

The right y-axis in Figure 3 is cast in terms of the radiative time constant appropriate for a given pressure in the atmosphere. While those for the pM Class range from only $10^3 - 10^4$ s, those for the pL Class range from $10^4 - 10^5$ seconds. This $\sim 10\times$ difference in timescale is a consequence of both the hotter temperatures and lower pressures of the pM Class photospheres, as can be understood from Equation 1.

One can also define an advective time scale, a characteristic time for moving atmospheric gas a given planetary distance. A common definition is $\tau_{\text{advec}} = \frac{R_p}{U}$, where U is the wind speed and R_p is the planet radius (Showman & Guillot 2002; Seager et al. 2005). If one sets $\tau_{\text{advec}} = \tau_{\text{rad}}$ and sets $R_p = 1R_J$, one can derive the wind speed U that would be necessary to advect atmospheric gas before a τ_{rad} has elapsed. This is also shown in Figure 3, via the gray bars on the right side. As previously discussed by Seager et al. (2005) and Fortney et al. (2006a), since the efficiency of energy redistribution and the depth to which one “sees” are wavelength dependent, the shape and times of maxima and minima in thermal emission light curves will be a function of wavelength.

Examination of Figure 3 shows that for a pM Class planet winds speeds of *dozens* of km s^{-1} would be necessary for advection to dominate over cooling/heating! For a pL Class planet more modest winds speeds of several km s^{-1} are needed. Several km s^{-1} winds are in line with predictions of a number of 2D and 3D dynamical models for hot Jupiter atmospheres (Showman & Guillot 2002; Cooper & Showman 2005; Langton & Laughlin 2007; Dobbs-Dixon & Lin

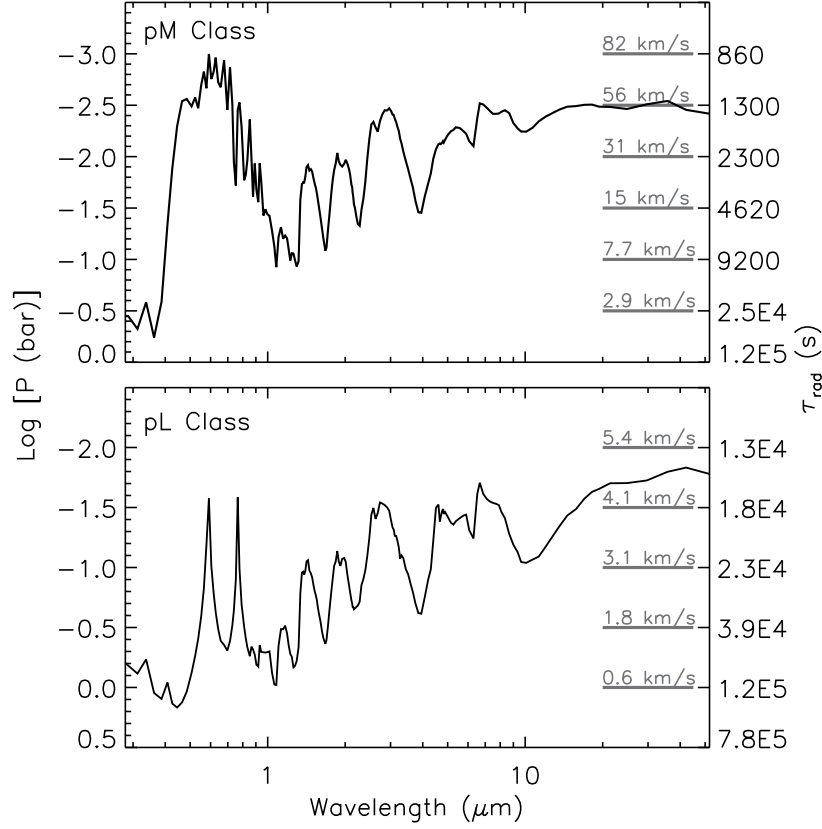


Figure 3. Both figures show, as a function of wavelength, the pressure that corresponds to a calculated brightness temperature. Note the differences in the y-axes. *Top*: Planet at 0.03 AU which has a stratosphere induced by absorption by TiO/VO. *Bottom*: Planet at 0.05 AU that lacks a stratosphere. The right ordinate (which is not linear) shows the corresponding radiative time constant at each major tick mark from the pressure axis. The labeled gray lines at right indicate an advective wind speed that would be necessary to give an advective time scale equal to the given radiative constant.

2007). These calculated wind speeds are far below those needed to advect air before it radiatively heats/cool in a pM Class atmosphere.

Winds will not be able to redistribute energy at the photospheres of pM Class planets. The atmospheres of pM Class planets likely appear as one would expect from radiative equilibrium considerations: the hottest part of the atmosphere is at the substellar point, and the atmosphere is cooler as one moves toward the planet's limb. The night-side temperature will be relatively cold and will be set by the intrinsic flux from the interior of the planet, as well as the efficiency of energy redistribution at depth. For a pL Class atmosphere, there will be a much more complex interplay between radiation and dynamics; energy redistribution may lead to a planetary hot spot being blown downwind. The location of the hot spot will itself be wavelength dependent, and there will be

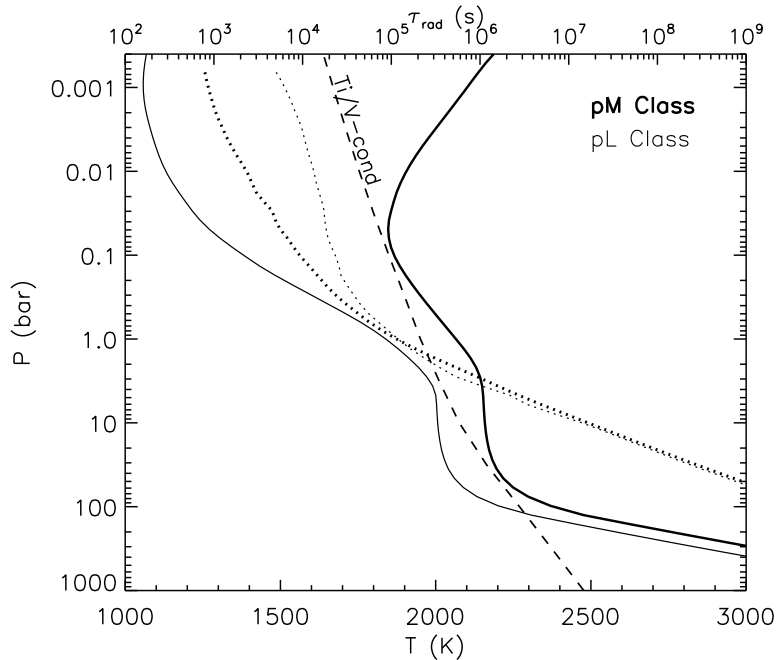


Figure 4. Pressure-temperature (solid lines, bottom x-axis) and pressure- τ_{rad} profiles (dotted lines, top x-axis) for the models at 0.03 AU (pM Class, thick lines) and 0.05 AU (pL Class, thin lines). Dashed curve shows Ti/V condensation.

increased energy transfer to the night side at photospheric pressures. Variability in secondary eclipse depth is a possibility (Rauscher et al. 2007). Recently Dobbs-Dixon & Lin (2007) have shown that larger day-night temperature differences are expected with increased atmospheric opacity, but they models lack motivation for their opacity choices. Dynamical models that do not include a realistic treatment of opacities and radiative transfer will miss the important differences between these two classes of planets.

3. Interiors

We now have a collection of at least 20 transiting gas giant planets, a smaller planet that is perhaps Neptune-like (GJ 436b), and a potential hybrid planet (HD 149026b, which is $\sim 2/3$ heavy elements, by mass). Very soon planets as small as $2 R_{\oplus}$ will be detected by COROT, and even smaller planets will be detected by Kepler. It is worthwhile to examine expectations for all of these classes of planets, and how these expectations are being challenged by observations.

3.1. Radii of Water-Rock-Iron Planets

It seems likely that planets with masses within an order of magnitude of the Earth's mass will be composed primarily of more refractory species, like the plan-

etary ices, rocks, and iron. Within our solar system, objects of similar radius can differ by over a factor of 3 in mass, due to compositional differences. A planet with the radius of Mercury, which is potentially detectable with Kepler, could indicate a mass of $0.055 M_{\oplus}$, like Mercury itself, or a mass of $1/3$ this value, like Callisto, which has a radius that differs by only 30 km. Fortney et al. (2007b) examined the radii of these planets, focusing on water/rock and rock/iron mixtures. These include pure water and water/rock mixtures, which could be described as “water worlds” or “Ocean planets.” Kuchner (2003) and Léger et al. (2004) have pointed out water-rich objects could reach many Earth masses (perhaps as failed giant planet cores) and migrate inward to smaller orbital distances. Fortney et al. (2007b) also consider planets composed of pure rock, rock and iron mixtures, and pure iron, more similar to our own terrestrial planets.

The results are shown in Figure 5. For all compositions, the radii initially grow as $M^{1/3}$, but at larger masses, compression effects become important. As a greater fraction of the electrons become pressure ionized, the materials begin to behave more like a Fermi gas, and there is a flattening of the mass-radius curves near $1000 M_{\oplus}$. Eventually the radii shrink as mass increases, with radii falling with $M^{-1/3}$ (see Zepolsky & Salpeter 1969). At the top left of Figure 5 we also show the size of various levels of uncertainty in planetary mass, as a percentages of a given mass, from 10 to 200%. For instance, if one could determine the mass of a $1 M_{\oplus}$ planet to within 50%, even a radius determination accurate to within $0.25 R_{\oplus}$ would lead to considerable ambiguity concerning composition, ranging from 50/50 water/rock to pure iron. The shallow slope of the mass-radius curves below a few M_{\oplus} makes accurate mass determinations especially important for understanding composition. We note that all models for water/rock/iron planets to date, be them simple (Fortney et al. 2007b; Seager et al. 2007) or complex (Ehrenreich et al. 2006; Valencia et al. 2006), give quite similar mass-radius relations, such that detailed models (that account for temperature effects and phase changes) do not appear to be necessary for determining likely bulk planetary composition (Seager et al. 2007; Fortney et al. 2007b).

From Figure 5 it is clear that planet GJ 436b cannot be composed purely of water. Ammonia and methane are slightly less dense than water, and may also be found within transiting planets, although they condense at colder temperatures. These three species are often termed “planetary ices” even though they may be found in any phase, not necessarily solid. It appears that GJ 436b must have a H/He envelope, like Uranus and Neptune. Furthermore, its radius is consistent with it *not* being the remnant of an evaporated gas giant (Fortney et al. 2007b). It is not possible to determine its composition in detail, as any water/rock ratio, with a variety of masses, with the remaining mass due to H/He, could lead to the observed radius. It is thought that Uranus and Neptune are composed mainly of the planetary ices in the dense warm fluid phase.

Since radial velocity or astrometric followup for even smaller planets will be extremely difficult and time consuming, radii may have to suffice as a proxy for mass for some time. Given an assumed composition, such as “Earth-like,” one could assign masses to terrestrial-sized transiting planets. The distribution of planetary masses vs. orbital distance and stellar type could then be compared with planet formation models.

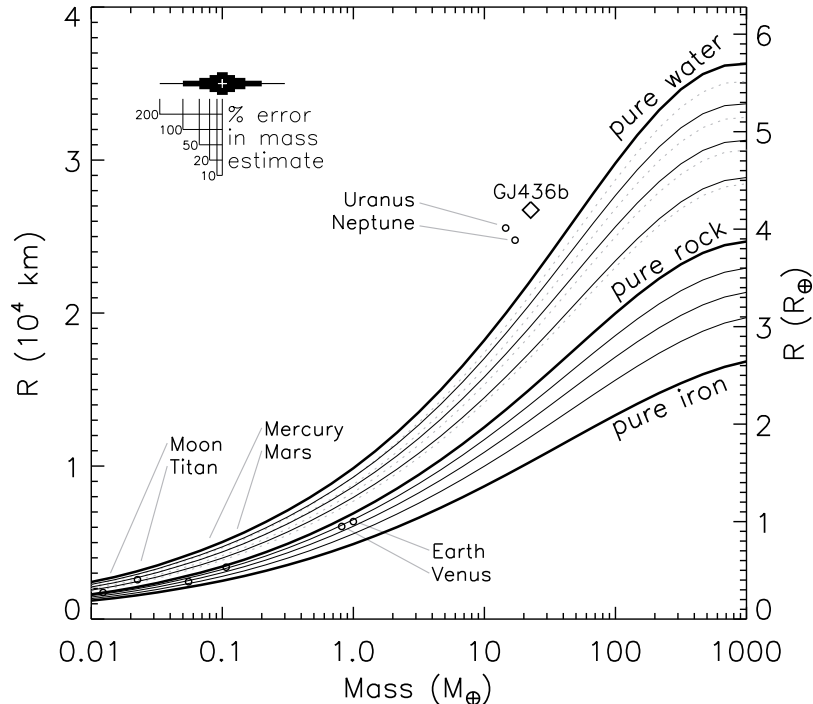


Figure 5. Mass (in M_{\oplus}) vs. radius (in km and R_{\oplus}) for planets composed for water, rock, and iron. The topmost thick black curve is for pure “warm” water. The middle thick curve is for pure rock (Mg_2SiO_4). The bottommost thick curve is for pure iron (Fe). The three black thin curves between pure water and pure rock, are from top to bottom, 75% water/25% rock, 50/50, and 25/75. The inner layer is rock and the outer layer is water. The gray dotted lines are the same pure water and water/rock curves, but for zero-temperature water. The three black thin curves between pure rock and iron, are from top to bottom, 75% rock/25% iron, 50/50, and 25/75. The inner layer is iron and the outer layer is rock. At the upper left we show the horizontal extent of mass error bars, for any given mass.

3.2. Radii of Gas Giants

Planets around the mass of Uranus and Neptune ($\sim 15 M_{\oplus}$) to objects as large at $75 M_J$ can be described by the same cooling theory. In general, planets with larger cores will have smaller radii, and planets closer to their parent stars will have larger radii at a given age than planets at larger orbital distances. From transit observations we seek to understand the abundance of heavy elements within a giant planet’s interior by comparing a measured mass/radius to theoretical calculations. It is not possible to determine if these heavy elements are within a core or distributed in the H/He envelope. Both Jupiter and Saturn have cores *and* supersolar abundances of heavy elements in their H/He envelopes. Even if Jupiter’s central core is very small, from its mass/radius it must possess 20-30 M_{\oplus} of heavy elements somewhere within its interior. Similar numbers are true for Saturn (Saumon & Guillot 2004). Given this knowledge,

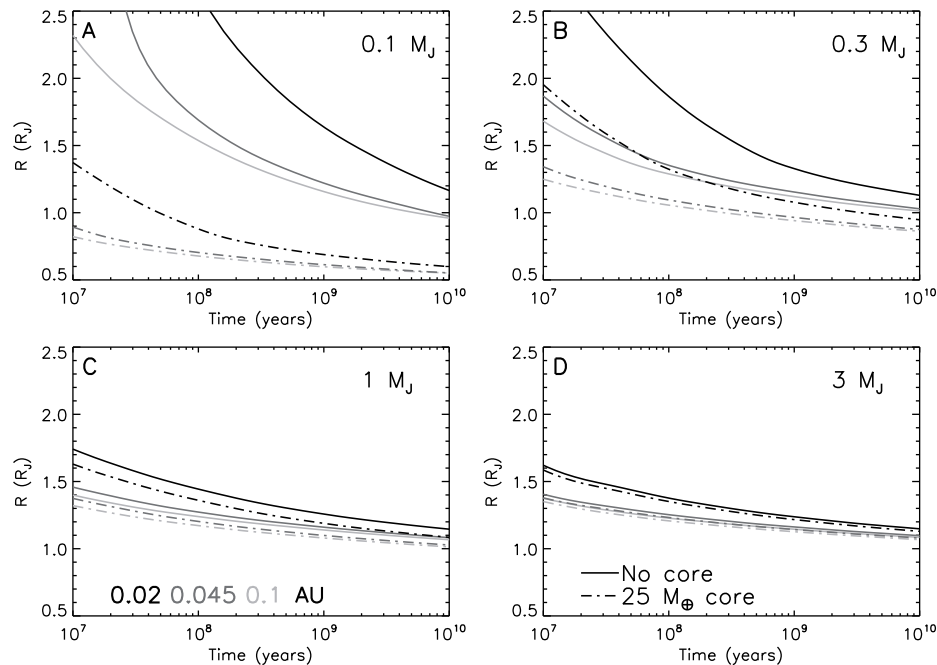


Figure 6. Planetary radii as a function of time for masses of $0.1 M_J$ ($32 M_\oplus$, A), $0.3 M_J$ (B), $1 M_J$ (C), and $3 M_J$ (D). The three shades code for the three different orbital separations from the Sun, shown in (C). Solid lines indicate models without cores and dash-dot lines indicate models with a core of $25 M_\oplus$.

1) it is very unlikely that the all heavy elements within a transiting giant planet are in the core, and 2) transiting planets (or any giant planets formed through core accretion) should not be expected to be pure H/He.

In Figure 6 we plot the contraction of planets from 0.1 to $3 M_J$, as a function of age at various orbital distances (Fortney et al. 2007b). We also show the effect of a core of $25 M_\oplus$, the approximate mass of heavy elements within Jupiter and Saturn (Saumon & Guillot 2004). Independent of mass, the spread in radii between 0.045 and 0.1 AU is small compared to the difference between 0.045 and 0.02 AU (see Fortney et al. 2007b). As expected, the effect of the $25 M_\oplus$ core diminishes with increased planet mass, as the core becomes a relatively smaller fraction of the planet’s mass. The radii at early ages it quite large, especially for the low-mass planets under intense stellar irradiation. These hot low-gravity planets are potentially susceptible to evaporation (Baraffe et al. 2004; Hubbard et al. 2007).

3.3. Current Explanations for Large Radii of Gas Giants

The standard cooling theory for giant planets (e.g., Hubbard et al. 2002) envisions an adiabatic H/He envelope, likely enhanced in heavy elements, on top of a distinct heavy element core, likely composed of ices and rocks. It is the radiative atmosphere that serves as the bottleneck for interior cooling and contraction.

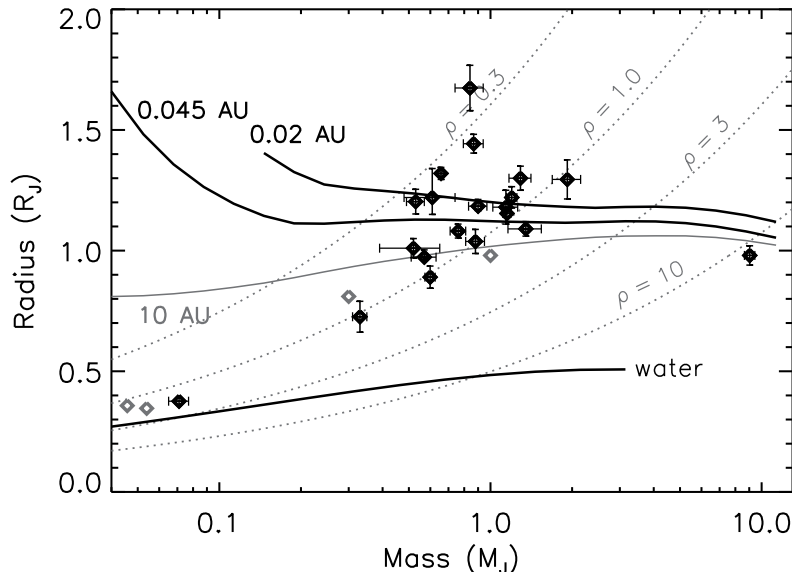


Figure 7. Planetary radii from the models of Fortney et al. (2007b) at 4.5 Gyr. The models are for a composition of pure H/He (which is likely unrealistic given the structure of Jupiter & Saturn), and includes the transit radius effect. Gas giant models were calculated at 0.02, 0.045 and 10 AU from the Sun. Diamonds without error bars or solar system planets.

As seen in Figure 6, at 4.5 Gyr it is not possible to have radii much in excess of $\sim 1.2 R_J$, even at 0.02 AU from the Sun, although at younger ages radii are larger. Nevertheless, as seen in Figure 7, several planets have radii in excess of $1.2 R_J$, and most receive irradiation far below that expected at 0.02 AU, as seen in Figure 2. Explaining the large radii has been a major focus of exoplanet research for several years. Below we briefly review the previous work.

- Bodenheimer et al. (2001) proposed that the radius of HD 209458b could be explained by non-zero orbital eccentricity, forced by an unseen additional planetary companion. This eccentricity would then be tidally damped, perhaps for gigayears. This is potentially ruled out by the timing of the secondary eclipse (Deming et al. 2005). But see also Mardling (2007).
- Guillot & Showman (2002) proposed that a small fraction ($\sim 1\%$) of absorbed stellar flux is converted to kinetic energy (winds) and dissipated at a depth of tens of bars by, e. g., the breaking of atmospheric waves. This mechanism would presumably effect all hot Jupiters to some degree.
- Baraffe et al. (2004) found that HD 209458b could be in the midst of extreme envelope evaporation, leading to a large radius, and we are catching

the planet at a special time in its evolution. The authors themselves judged this to be very unlikely.

- Winn & Holman (2005) found that HD 209458b may be stuck in a Cassini state, with its obliquity turned over at 90 degrees, which leads to a tidal damping of obliquity over gigayear ages. Recently Levrard et al. (2007) and Fabrycky et al. (2007) have cast serious doubt on this mechanism.
- Burrows et al. (2007b) propose that atmospheres with significantly enhanced opacities ($10\times$ that of a solar mixture) would stall the cooling and contraction of the planetary interior, leading to larger radii at gigayear ages. Spectra of hot Jupiter atmospheres will either support or refute this (currently ad-hoc) possibility.
- Chabrier & Baraffe (2007), independently following along the lines of a hypothesis from Stevenson (1985), suggest that gradients in heavy elements (such as from core dredge-up or dissolution of planetesimals) could suppress convection and cooling in the H/He envelope, leading to large radii at gigayear ages. The effect could be present at any orbital distance.
- Hansen & Barman (2007) suggest that if mass loss due to evaporation leads to a preferential loss of He vs. H (perhaps due to magnetic fields confining H^+), that planets could be larger than expected due to a smaller mean molecular weight. This mechanism would also presumably effect all hot Jupiters to some degree.

We note that a planetary embiggening mechanism that would affect all hot Jupiters is perfectly cromulent. Since giant planets are expected to be metal rich (Jupiter and Saturn are 5-20% heavy elements) a mechanism that would otherwise lead to large radii could easily be canceled out by a large planetary core or a supersolar abundance of heavy elements in the H/He envelope in most planets (Fortney et al. 2006b). Planets that appear “too small” are certainly expected and are relatively easy to account for due to a diversity in internal heavy elements abundances (Guillot et al. 2006; Burrows et al. 2007b). It is important to recall that all these evolution models neglect (to the best of our knowledge) the strong opacity of TiO/VO on the hottest planets, which may alter their cooling history and will lead to a larger optical transit radius (Fortney et al. 2007a; Burrows et al. 2007c). This avenue will need to be explored.

4. Conclusions

The future will surely see additional discoveries in atmospheric and interior physics. In particular, a large amount of *Spitzer* data on atmospheric thermal emission is just beginning to be published. Thermal emission light curves, as a function of orbital phase, will take on increased importance. Mass/radius determinations for less irradiated giant planets will test theories for planetary evolution. Certainly the next frontier is smaller masses, now that GJ 436b is known to transit (Gillon et al. 2007). Paced by discoveries from space missions

(such as *COROT* and *Kepler*) and ground-based surveys, as well as precise followup characterization observations via *Spitzer*, *Hubble*, *MOST*, and the ground, the future is even more exciting than the present.

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